Imagery-derived modulation transfer function and its applications for underwater imaging

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ABSTRACT

The main challenge working with underwater imagery results from both rapid decay of signals due to absorption, which leads to poor signal to noise returns, and the blurring caused by strong scattering by the water itself and constituents within, especially particulates. The modulation transfer function (MTF) of an optical system gives the detailed and precise information regarding the system behavior. Underwater imageries can be better restored with the knowledge of the system MTF or the point spread function (PSF), the Fourier transformed equivalent, extending the performance range as well as the information retrieval from underwater electro-optical system. This is critical in many civilian and military applications, including target and especially mine detection, search and rescue, and diver visibility. This effort utilizes test imageries obtained by the Laser Underwater Camera Imaging Enhancer (LUCIE) from Defense Research and Development Canada (DRDC), during an April-May 2006 trial experiment in Panama City, Florida. Imaging of a standard resolution chart with various spatial frequencies were taken underwater in a controlled optical environment, at varying distances. In-water optical properties during the experiment were measured, which included the absorption and attenuation coefficients, particle size distribution, and volume scattering function. Resulting images were preprocessed to enhance signal to noise ratio by averaging multiple frames, and to remove uneven illumination at target plane. The MTF of the medium was then derived from measurement of above imageries, subtracting the effect of the camera system. PSFs converted from the measured MTF were then used to restore the blurred imageries by different deconvolution methods. The effects of polarization from source to receiver on resulting MTFs were examined and we demonstrate that matching polarizations do enhance system transfer functions. This approach also shows promise in deriving medium optical properties including absorption and attenuation.

Keywords: image restoration, ocean optics, polarization, MCM, MTF

1. BACKGROUND

One key application and research topic of digital image processing is the enhancement and restoration using carefully designed filters, based on scene contents[1]. Although traditional image enhancement techniques can be used for images obtained from underwater environments, without knowledge of any processes involved nor the optical properties, the effectiveness is considerably restrained. Due to complex environmental variability arising from different water types and associated in-water optical properties, the ability to generally extend the performance range as well as the information retrieval from underwater electro-optical system is critical for many civilian and military applications. These include target and mine detection, search and rescue, and diver visibility. The main challenge working with underwater imagery results from both rapid decay of signals due to absorption, which leads to poor signal to noise returns, and the blurring caused by strong scattering by the water itself and constituents within, especially various sized particulates. To properly address this issue, knowledge of in-water optical properties and their relationship to the image formation can be exploited in order to restore the imagery to the best possible level. Such effects have been examined by various researchers early on[2-4] from a scattering perspective, and recently from imaging needs[5-7]. The method provides much needed environmental information via through-the-sensor techniques [6, 7] and greatly enhance current operational capabilities. As these studies show, the knowledge of system response can be modeled by in-water optical properties. Alternatively, one can measure the system response function at various spatial frequencies by examining the corresponding resolution chart at different distances directly. The imagery-derived response function can then be

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14. ABSTRACT
The main challenge working with underwater imagery results from both rapid decay of signals due to absorption, which leads to poor signal to noise returns, and the blurring caused by strong scattering by the water itself and constituents within, especially particulates. The modulation transfer function (MTF) of an optical system gives the detailed and precise information regarding the system behavior. Underwater imageries can be better restored with the knowledge of the system MTF or the point spread function (PSF), the Fourier transformed equivalent, extending the performance range as well as the information retrieval from underwater electro-optical system. This is critical in many civilian and military applications, including target and especially mine detection, search and rescue, and diver visibility. This effort utilizes test imageries obtained by the Laser Underwater Camera Imaging Enhancer (LUCIE) from Defense Research and Development Canada (DRDC), during an April-May 2006 trial experiment in Panama City, Florida. Imagings of a standard resolution chart with various spatial frequencies were taken underwater in a controlled optical environment, at varying distances. In-water optical properties during the experiment were measured, which included the absorption and attenuation coefficients, particle size distribution, and volume scattering function. Resulting images were preprocessed to enhance signal to noise ratio by averaging multiple..

15. SUBJECT TERMS
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modeled, and further applied to restore images. We briefly outline the theoretical background, followed by a discussion of measurement results.

2. MODULATION TRANSFER FUNCTION

Briefly, an image of an object is the convolution of original signal, $f(x,y)$ with the imaging system response of a point source, the point spread function or PSF $h(x,y)$, with added noise $n(x,y)$:

$$g(x, y) = f(x, y) \otimes h(x, y) + n(x, y),\tag{1}$$

here $\otimes$ denotes 2-D convolution, and $h(x,y)$ is the system response to a point source, or the point-spread function (PSF). The system response includes those from both the imaging system itself, as well as the effects of the medium (water in our case).

In the frequency domain, the convolution operator becomes a simple multiplication. Applying a Fourier transform, the above relationship becomes

$$G(u, v) = F(u, v)H(u, v) + N(u, v),\tag{2}$$

here u, v are spatial frequencies and G, F, H, N are Fourier transforms of g, f, h and n respectively. The Fourier transfer of h, for example, takes on the following form:

$$H(u, v) = \int\limits_{-\infty}^{\infty} \int h(x, y)e^{-j2\pi(ux+vy)}dxdy,\tag{3}$$

The system response function H in frequency domain, also referred to as the optical transfer function (OTF), is the Fourier transform of the PSF and the magnitude of the OTF is the modulation transfer function (MTF). The MTF describes the contrast response of a system at different spatial frequencies, and when the phase information is of little concern as is the case for typical incoherent systems, it is a sufficient measure of the power transfer. Notice that the above MTF term $H(u,v)$ is the total system response. Therefore if one views the complete path from target to the bottom of our eyes or the recording CCD plane, the MTF is the effect of multiple individual components. Because of the cascading nature of the MTF, in the frequency domain, it can be expressed by the direct product of each component, for instance, the optical system itself, and the medium (plus any other factors when applicable):

$$H(u, v) = H_{system}(u, v)H_{medium}(u, v).\tag{4}$$

The above formulation, which emphasizes the validity of the separation of the system and the medium, is important in our analysis. Usually the system response $H_{system}(u,v)$ can be pre-determined and calibrated to remove any significant errors, and in most cases, does not vary with imaging conditions. From (2), one can see that with the knowledge of system MTF $H(\mu,v)$ and transformed image output $G(\mu,v)$, the original image can be theoretically restored by deconvolving the effect in frequency domain to obtain the unblurred version after inverse transform.

Needless to say, the presence of noise from various sources (such as scattering or surface fluctuations) complicates these through-the-sensor techniques. They represent the extra term in both (1) and (2). The medium effect is two fold: scattering would contribute extra blurring on top of system response, while attenuation results in reduced signal-to-noise ratio. Different image restoration approaches exist to reduce and compensate for the noise to deblur images, such as Wiener, Lucy-Richardson and blind deconvolutions[1]. A denoising algorithm based on wavelet decomposition has been developed [5] and can be applied to underwater imagery, while image quality can be assessed more accurately at the same time.

For an isotropic volume scattering type found in the seawater, the corresponding 2-dimensional transforms found in (3) can be reduced to a one-dimensional Hankel (Fourier-Bessel) integral,

$$H(\psi, r) = 2\pi \int\limits_{\theta=0}^{\theta_{max}} J_0(2\pi\theta\psi)h(\theta, r)\theta d\theta.\tag{5}$$

Wells [2] applied small angle approximations to the above and derived a robust underwater modulation transfer model which is briefly outlined below. By separating the exponential decay effect with distance due to the medium, the MTF of the medium in (4) can be expressed as

$$H_{medium}(\psi, r) = e^{-D(\psi)r}, \tag{6}$$

where $D(\psi)$ is the decay transfer function (DTF) and is independent of the range of detection. This provides a method to compare measurements at different ranges for consistency.

By using a thin slab model with the small angle scattering approximation, and assuming a simple phase function,

$$\beta(\theta) = \frac{b\theta_0}{2\pi(\theta_0^2 + \theta^2)^{3/2}}, \tag{7}$$

Wells [2] showed that the DTF of the seawater can be expressed as

$$D(\psi) = c - \frac{b(1 - e^{-2\pi\theta_0\psi})}{2\pi\theta_0\psi}. \tag{8}$$

θ_0 is related to the mean square angle (MSA), b is the total scattering coefficient, and c is the total attenuation coefficient [8]. It has been shown that the exact shape of the scattering phase function does not affect the derived results [9]. With the imaging range defined, the medium MTF can be obtained from (6). Alternatively, by the definition of MTF, one can measure directly the system response from calibrated imagery at various spatial frequencies. The above mentioned equation will then enable us to determine the DTF from imagery-derived MTF. Theoretically, this allows calculations of MTF at different ranges following (6), which can be further used to deconvolve any imagery obtained under the same condition for restoration.

3. IMAGERY-DERIVED MTF AND APPLICATIONS

Test image sets were obtained using the Laser Underwater Camera Imaging Enhancer or LUCIE from Defense Research and Development Canada (DRDC), during an April-May 2006 NATO trial experiment in Panama City, Florida. The amount of scattering and absorption were controlled by introducing Maalox and absorption dye respectively. Although the effects of polarizations were examined during the experiment, all images used in this study are unpolarized. In-water optical properties during the experiment were measured. These included the absorption and attenuation coefficients (Wetlabs ac-9), particle size distributions (Sequoia Scientific LISST-100), and volume scattering functions (multi-spectral volume scattering meter or MVSM).

The measured MTFs of lens and LUCIE camera system are used to model the combined system MTF ($H_{system}(\mu, v)$ in (4)), which is shown in Fig. 1, modeled by a Gaussian point response ($R^2 > 0.99$ in all fits). It is clear that the camera is the limiting factor in the system setup. This modeled system response function is used later with all imagery-derived MTF in order to derive MTF of the water using (4).

Images from two distinctive water types were used to obtain direct MTF measurements. They are from April 28 morning and afternoon, with absorption a~0.038 and b~0.35 m^{-1}, and May 3rd morning (a~0.27, b~0.95). The ranges of target are between 3.7m to 7.1m. Test imageries are digitized at 8bit 640x480 pixel resolution, and are the result of 15 averaged frames for April 28 data and 64 frames for May 3.

Based on the approach discussed above, we measured the contrast transfer functions (CTF) of resolution chart imageries from LUCIE. MATLAB® routine provided by FOI (Swedish Defense Research Agency) is modified to include flat-fielding to remove uneven illumination at target plane, denoising[5], before CTFs are measured. For initial proof of concept, we ignore the differences between CTF and MTF as the differences is small compared to the measurement variations[10]. The measured DTFs are shown in Figs. 2, under different conditions. Notice that each data point shown in the figure is measured using multiple (>20) pixels which is the result of averaged multi-frames to increase signal-to-noise ratio.
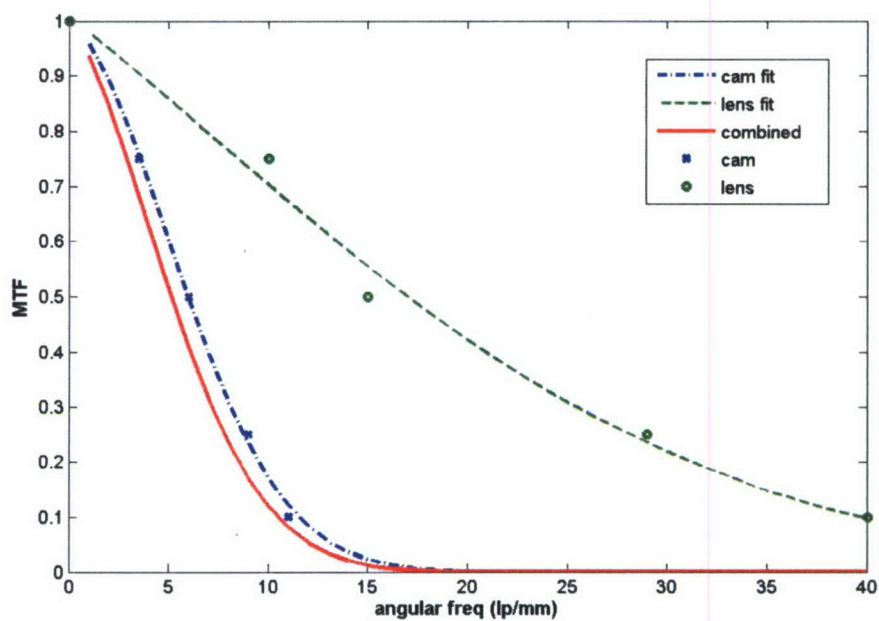
Figure 1. Overall camera system (lens plus camera) MTF. Measured camera and lens MTF were used in Guassian-type fits.
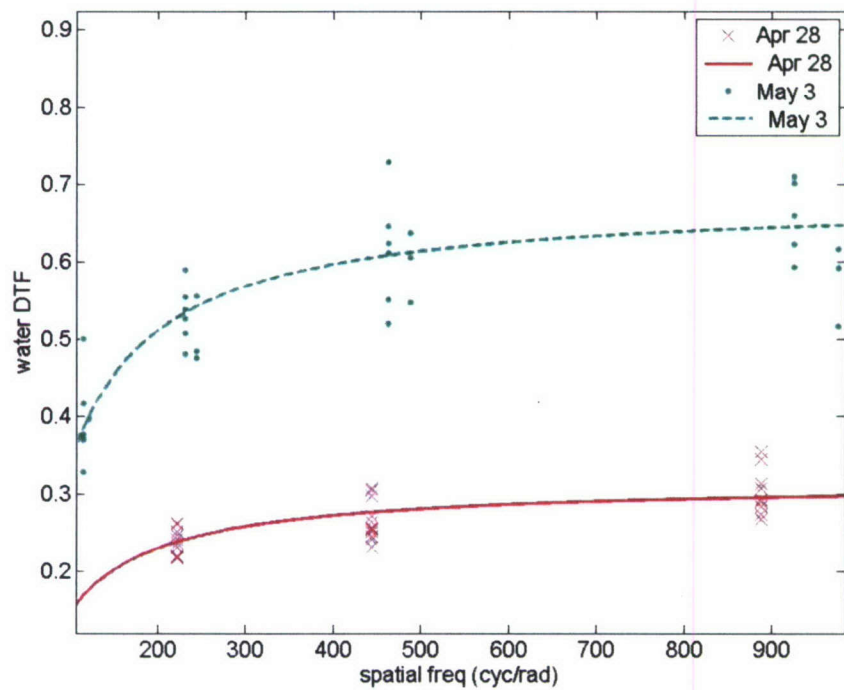

Figure 2. Sample result of retrieved optical properties from measured MTFs based on Wells' small angle scattering theory. Top and bottom curves correspond to turbid (c=0.95 m^{-1}) and clear (c=0.35) conditions respectively.

The measurement results are then fitted with the following regression equation form, following (8)

$$D(X) = C + \frac{A(1 - e^{-X})}{X} \tag{9}$$

with regression results shown in Figs. 2-3. The regression parameters for the clearer water are A=-16.79 and C=0.3139. For the turbid condition, they are A=-34.35 and C=0.6822.

In addition, it is straightforward to obtain medium optical properties from the imagery-derived DTF by applying the first order Taylor expansion to the exponent for under Wells' formulation (8),

$$D(\psi \to 0) = c - \frac{b(1 - e^{-2\pi\theta_0\psi})}{2\pi\theta_0\psi}$$
$$= c - \frac{b(1 - 1 + 2\pi\theta_0\psi)}{2\pi\theta_0\psi} \tag{10}$$
$$= c - b = a$$
$$D(\psi \to \infty) = c - \frac{b(1-0)}{\infty} = c$$

This approach would yield c=0.31 m^{-1} for the clear water situation, inline with the measured value (c=0.35 m^{-1}). For the turbid situation the regression yields c=0.68 m^{-1}, which is smaller compared to the measured value of 0.95 m^{-1}. For absorption under the turbid condition, the regression trend is close to the field measured a=0.36 m^{-1} at low angular frequencies (Fig. 2). Due to the uncertainties associated with the limited data available, a small deviation in high frequency samples can easily affect the trend in the regression. Uneven illumination can also be observed in raw images (eg. Fig.4a), which contributes in part to the scatter of data points in the derived results shown in Figs. 2-3, even though flat-fielding was applied based on the overall illumination pattern. Errors in denoising also likely contributed to the fluctuations observed. Under the current setup, this method should best be taken as a proof of concept since many uncertainties still remain.

The effect of the polarization was also examined during the trial experiment. Imagery was obtained from a resolution target (2 to 256 mm/lp) with unpolarized, vertically polarized, and circular polarized source and receiver. Mismatching polarizations between source and receiver were also tested in the field. However, resulting imagery do not provide meaningful target information and therefore not used in this study. Comparisons between unpolarized (U), matching vertical-polarized (V) and circular-polarized (C) results are shown in Fig. 3, using imagery from April 28 (clearer water, b=0.35 m^{-1}) and May 3 (more turbid, b=0.95m^{-1}). Results show that the unpolarized setup returned higher DTFs compared to the polarized, in all 3 cases tested (ie at 7.1m in clear water, 3.7m and 4.9m in more turbid). Although not conclusive, considering limited data collected, it confirms that polarized illumination is better for underwater imaging, which is intuitively understandable since less scattered ambient light is accounted for. We also notice that at longer optical length, errors increase significantly such that regression correlations perform poorly. For example, the goodness of fit (R^2) is as low as 0.16 at 4.7m (thus not shown), comparing to 0.80 at 3.9m on May 3.

Clearly the above result can benefit from measurements at increased spatial frequencies. One distinctive flaw observed from Figs. 2-3 is the lack of sampling data at finer spatial frequencies. This is, in part, an inherent effect of the current system setup which only has low resolution (640x480 digitization), and a limited field of view. By carefully arranging different targets, it is possible to have higher sampling rates at frequencies. Alternatively, approaches such as those used for in-orbit sensor calibration and measurement can be applied[11]. Higher dynamic ranges (such as L3CCDs with higher bit width) will also help to eliminate probable digitization errors which are apparent in Figs. 2-3.

Imagery-derived MTF by this approach is used in restoration of underwater images, following (1) and (2) with Fourier transferred MTF (ie the point spread function, PSF). A sample restoration image of LUCIE imagery taken on Apr 28 is shown in Fig. 4. Notice that the visual differences between the restored images based on the current MTF method and model-based approach, likely the result of differences at high frequency end as discussed above. More details can be found in [6].
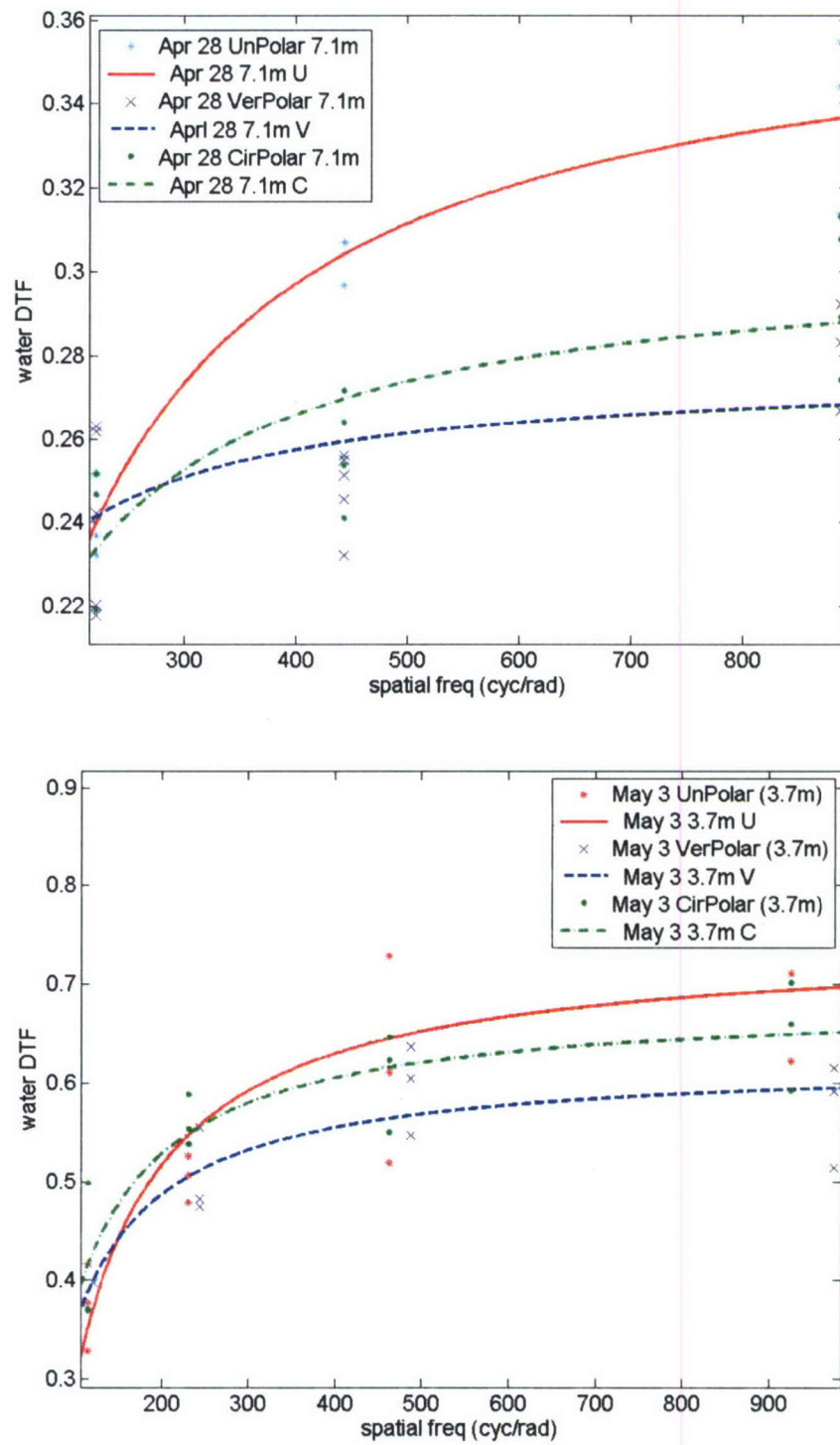
Figure 3. Comparison of image-derived water DTF under different polarization conditions (U: unpolarized; V: vertical polarized; C: circular polarized), on two different days. Notice consistently higher DTFs are observed for unpolarized light source and receiver pairs on both days.
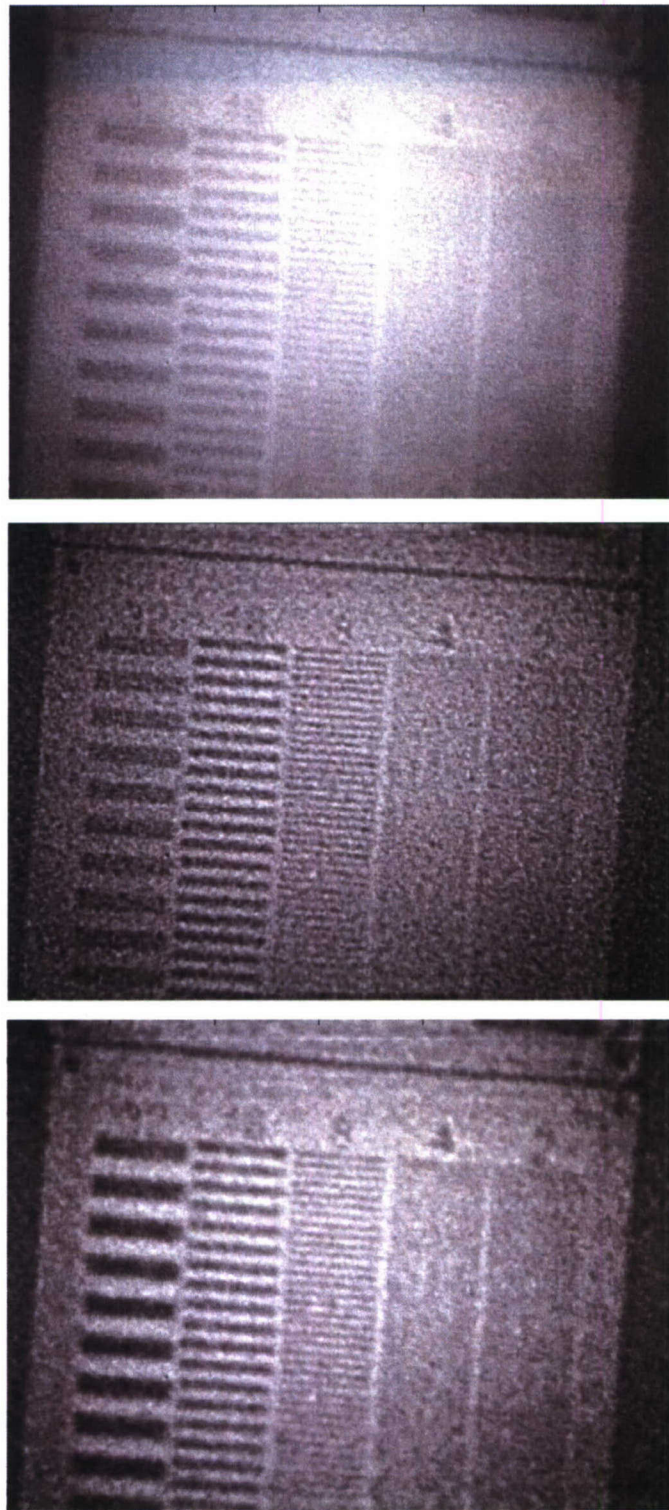
Figure 4. Sample LUCIE imagery taken on April 28 at 7.5m showing a) the original (top), b) the restored image based on measured MTF (middle), and c) the restored image based on modeled MTF (bottom). Notice uneven illumination on the raw image.

3. CONCLUSION

The modulation transfer functions of the medium (water) were derived using direct measurement of various spatial frequency response from underwater imagery, excluding the influence of the camera system. It is shown that this approach agrees with a model based on small angle approximations. Such derived transfer function is then used to restore the imagery and demonstrate improved restoration. Polarization efforts were also examined in this study. While not conclusive, it shows that source and receiver polarization does enhance system transfer function. Lastly initial results presented support the effectiveness of our imaging analysis framework even though further improvements are needed to improve restoration quality with better sampling at finer spatial frequencies.

4. ACKNOWLEDGEMENTS

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